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Proper Core Numbering and Clarification of Polarity Concepts for Polarity-Management-Free 4-Core Multicore Fiber Connections

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***Abstract*—We present that a proper core numbering pattern can simplify the consideration on the polarity-management-free multicore fiber connections in bidirectional transmissions, and also discuss the difference of connection polarity and cable/fiber polarity for clearer discussions in future studies on multicore fiber connections.**

***Keywords*—multicore fiber, bidirectional transmission, connection polarity, core numbering**

I. Introduction

Space division multiplexing (SDM) is a promising technology to increase the transmission capacity of optical networks [1], and the multicore fiber (MCF) has been finally commercialized for submarine applications [2], with ultralow-loss uncoupled 2-core fiber [3,4]. The 2-core fiber can be realized with completely polarity-free core layout with asymmetric core arrangement without any single-purpose marker [3,4]. For further scaling of the core count in MCFs, 4-core fibers can be the next step from the 2-core fiber. For ultralow-loss transmission media for long-haul transmissions, coupled 4-core fiber can be a strong candidate thanks to its volume-production suitable optical fiber structure [5,6], with accepting the random mode coupling between the core that can be compensated by multiple-input-multiple-output (MIMO) digital signal processing (DSP). The coupled MCFs can also realize completely polarity-free core layouts without any markers because the coupled MCFs do not need core identification, thanks to the MIMO DSP. This is similar to the standard single-mode fibers, which do not require any polarization identification markers, where polarization mode coupling is compensated by 2x2 MIMO DSP in digital coherent transmissions.

On the other hand, uncoupled MCFs are also attractive transmission media especially for short-reach or terrestrial applications [7–10], because of its compatibility to the conventional transceivers for single-mode fibers. Within a standard 125-µm cladding, 4 cores can be packed with suppressed inter-core crosstalk (XT) in C band [7,11]. To realize uncoupled MCF links more economically, bidirectional transmission within a single MCF with the propagation direction interleaving between nearest neighboring cores is quite beneficial to suppress the inter-core crosstalk (XT) of MCF transmission systems [9,12,13], and to relax the low XT requirements for uncoupled MCFs.

To build an uncoupled 4-core fiber system, one may consider the management of the connection polarity of the 4-core fiber can be a challenge [14]. However, in most terrestrial optical fiber links, we do not need exact core number matching or maker-side matching (Imagine whether your applications require precise management of the optical characteristics of each core by concatenating optical fibers preassigned based on their optical characteristics variations or you are just fine if every core is within the specifications. Also imagine whether or not you think about the fiber ID numbers in MPO connectors when you connect MPO connectors.). In such cases, we can realize polarity-management-free MCF connections with proper line symmetric MCF core layouts [9,15,16]. However, various types of core numbering have been used in literature [13,14,17–20], and some of them may not be suitable for the discussions on polarity-management-free MCF connections.

In this study, we investigate the patterns of the core numbering of the 4-core fiber, and show that the proper core numbering with the circular numbering trace that traverse the symmetric axis between Core 2 and Core 3 is helpful for intuitive understanding of the polarity-management-free MCF connections, and the other numbering would overcomplicate the discussion. We also discuss the difference between connection polarity and cable/fiber polarity, which can be confusing because the different concepts are discussed using similar words.

II. Polarity-Management-Free Connection of 4-Core Fiber Compatible to Bidirectional Transmissions

The connection polarity management of 4-core fibers can be avoided by the line symmetric core layouts w.r.t. the line through the cladding center [9,17,21]. In this section, we briefly review the polarity-management-free connection in the case of the 4-core fiber.

Figure 1 shows the schematics of the 4-core fiber with line symmetric core layout without any cores on the symmetric axis, which enables identical FIFO routing and/or TRx layout at different ends. In Fig. 1, the "key" direction is the center line (symmetric axis) direction toward the marker. Unique core ID layout is inverted w.r.t. the center line between the two ends of the MCFs. If you have to keep the same unique core ID through a link, different ends (End L–End R) connection is necessary [Fig. 2(top)]. However, by accepting the core ID transpose at opposite ends (like Type B polarity of MPO), the same ends can be connected without considering polarity [Fig. 2(bottom)]. For example, as shown in Fig. 3, if we use *port* IDs like "L*n*" for the left cores and "R*n*" for the right cores

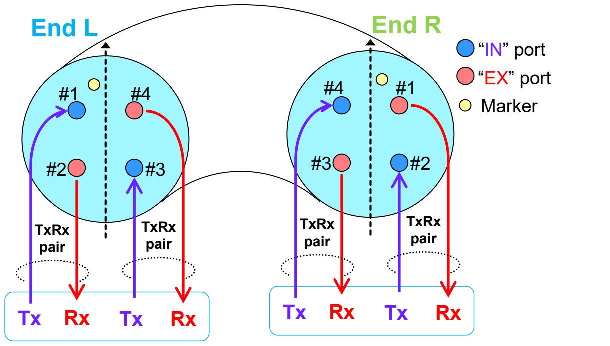

Fig. 1. The 4-core fiber with line symmetric core layout without any cores on the symmetric axis, which enables identical FIFO routing and/or TRx layout at different ends [17]. Black digits: unique core ID, dashed arrows: the center lines (symmetric axis) with a key direction. End A/B in [17] are replaced by End L/R (same in Figs. 2,3).

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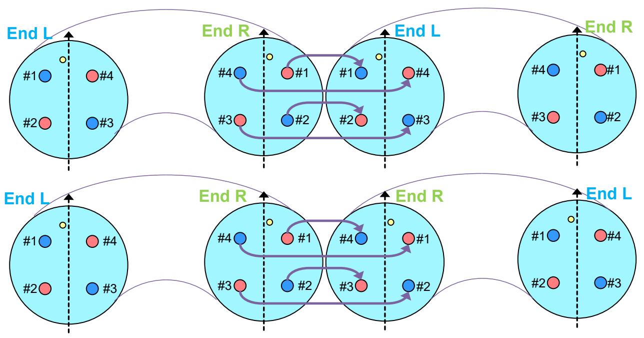

Fig. 2. Core ID matching of the 4-core fiber in the different end connection (top) and in the same end connection (bottom). Unique core ID can be preserved at the different end connection, but not in the same end connetion. [17,21].

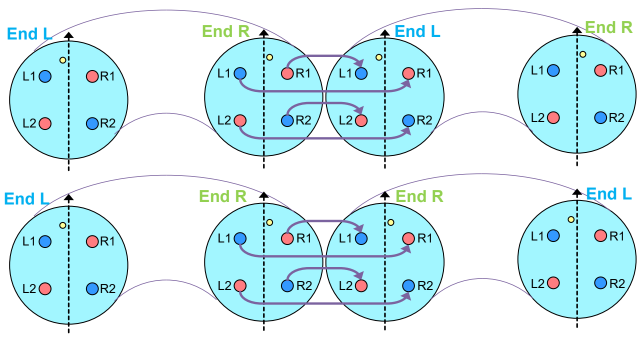

Fig. 3. Port ID matching of the 4-core fiber in the different end connection (top) and in the same end connection (bottom). Ln cores at one end are always Rn cores at the other end. Rn port and Ln port are always matched either at the different/same end connection. [17,21].

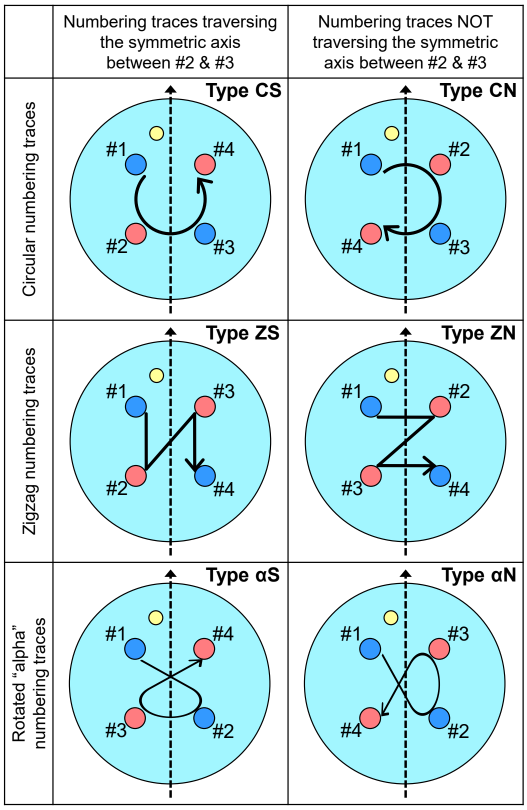

Fig. 4. Six representative types of the core numbering in the 4-core fiber with square core layout. Black arrows: the traces of core numbering from Core 1 to Core 4. Dashed purple arrows: the symmetric axis of the line-symmetric core layout.

from the center line at each end, the core with port Ln at one end is the same with the core with port Rn at the other end, and port Ln are always mated to port Rn either in the same end connection or different end connection.

III. Types of the Core Numbering of the 4-Core Fiber with Line-Symmetric Core Layout

As mentioned above, port IDs can simplify the consideration on the polarity-management-free MCF connections. However, proper unique core ID numbering also greatly helps intuitive understanding of polarity-management-free MCF connections. Therefore, we investigate the types of core numbering and how they affect the simplicity of the discussion on polarity-management-free MCF connections.

Though there are 24 patterns of the core numbering of the 4-core fiber (the permutation of 4 is 4! = 24), the 24 core numbering patterns can be reduced to 6 types in the view of shapes and symmetricity of the numbering traces from Core 1 to Core 4, as shown in Fig. 4. The 6 types can be divided into 2 types by whether or not the numbering traces traverse the symmetric axis between Core 2 and Core 3, and 3 types by the shapes of the numbering traces (circular trace, zigzag trace, and rotated alpha shape trace). In this paper, we name the 6 types as CS, ZS, αS, CN, ZN, and αN. The first character C/Z/α represents the shape of the numbering traces (circular, zigzag, or alpha). The second character S/N represents whether the trace traverses the symmetric axis between Core 2 and Core 3 or not. Note that the core numbering in Figs. 1,2 is Type CS. We can find Type CS core numbering in [13,17,19,20], and Type CN in [14,18,22]. In the numbering traces shown in Fig. 4, Core 1 is nearest to the marker, but there are 3 other variations for each type, which can be obtained by horizontally and/or vertically flipping the trace pattern shown in Fig. 4. However, we ignore such variations because most discussions can be covered by the 6 numbering trace patterns shown in Fig. 4.

Now, we consider how they affect the discussion simplicity of the polarity-management-free MCF connections. Because the polarity-management-free MCF connections utilize the horizontal flip of the line symmetric core layout between both ends of MCFs, some kind of *symmetricity* of core numbering traces significantly improve the discussion simplicity. Table 1 shows the unique core IDs at both ends of the 4-core fiber, corresponding to the Ln-Rn port numbering. Obviously, Type CS is the simplest core numbering to consider the symmetric polarity-management-free MCF connections, where monotonically increasing/decreasing core numbers are just reversed between different ends. In this case, Cores 1 and 2 correspond to Port L1 and L2 at End L, and Port R1 and R2 at End R, as you can see in Table 1 and can understand by comparing Figs. 2,3. This is also obvious, but another advantage of Type CS (or circular shape numbering traces) is that two cores in every pair of nearest neighboring cores has consecutive core IDs (including Cores 4 and 1 in a

TABLE I. Unique Core IDs Corresponding to Port IDs, in Each Core Numbering Types

Type	End	Port L1	Port L2	Port R2	Port R1
CS	L	1	2	3	4
	R	4	3	2	1
ZS	L	1	2	4	3
	R	3	4	2	1
αS	L	1	3	2	4
	R	4	2	3	1
CN	L	1	4	3	2
	R	2	3	4	1
ZN	L	1	3	4	2
	R	2	4	3	1
αN	L	1	4	2	3
	R	3	2	4	1

TABLE II. UNIQUE CORE IDS OF OPPOSITE/SAME PROPAGATION DIRECTION PAIRS, IN EACH CORE NUMBERING TYPES

Type	Nearest neighboring pairs (opposite propagation direction pairs)			Same propagation direction pairs
	All pairs	*Vertical pairs*	*Horizontal pairs*	
CS	1–2, 2–3,	1–2, 3–4	2–3, 4–1	1–3, 2–4
CN	3–4, 4–1	2–3, 4–1	1–2, 3–4	
ZS	1–2, 1–3,	1–2, 3–4	1–3, 2–4	2–3, 4–1
ZN	3–4, 2–4	1–3, 2–4	1–2, 3–4	
αS	1–3, 2–3,	1–3, 2–4	2–3, 4–1	1–2, 3–4
αN	2–4, 4–1	2–3, 4–1	1–3, 2–4	

cyclic sequence), which is also helpful for identifying high-crosstalk pairs (or opposite propagation direction pairs in bidirectional transmissions) of the cores. This is summarized in Table 2, where red characters with underlines represent irregularity. The numbering orders of other *symmetric* types (ZS, αS) are still somewhat systematic but more complicated numbering orders compared to type CS; therefore, there are no strong reasons to select these numbering types instead of the simplest CS type for considering the polarity-management-free MCF connections. The nonsymmetric types (CN, ZN, and αN) have further random numbering orders and are not suitable for the discussion on polarity-management-free MCF connections.

As discussed above, Type-CS core numbering (and Ln-Rn port numbering) is suitable for the polarity-management-free MCF connections. However, it is just a formal numbering problem and does not change anything on the physical properties of MCFs. Therefore, if you already have MCFs with the non-CS-type core numbering, you can just convert their core numbering type to Type CS by replacing the existing core IDs by Type-CS core IDs, for more intuitive management of your MCF links.

IV. CLARIFICATION OF POLARITY CONCEPTS IN MCF LINKS

The polarity discussed above and discussed in [9,14,15] is connection polarity (correct/wrong orientations of cables/fibers), which should be distinguished from cable/fiber polarity (in what pattern and order the fibers/cores are arranged at two terminated ends of a cable/fiber). For instance, the concept of "straight connection" and "cross connection" were introduced in [14], where the MCF connection between the different ends [Fig. 2(top)] is referred to as a "*straight* connection", and the connection between the same ends [Fig. 2(bottom)] is called a "*cross* connection". However, we should note that these *straight* and *cross* connections are different from the concept of *straight* cable (straight-through cable: multiple fibers/cores are terminated in the same order in the fiber ports of the connectors at both ends of the cable, i.e., the same fiber goes to the same port at both ends, e.g., Type A in MPO cable) and *reversed* cable (a type of *cross/crossover* cable: multiple fibers/cores are terminated in the opposite order at different ends of the cable, e.g., Type B in MPO cable), respectively. When discussing the polarity of an MPO cable, such as Type A polarity or Type B polarity, the polarity being discussed is the cable/fiber polarity. As discussed in Section 2, regardless of the *connection* polarity (*straight* or *cross*), a 4-core fiber with a line-symmetric core layout can achieve MCF connections without connection polarity management. On the other hand, the *cable/fiber* polarity of the 4-core fibers in [9,14,15] is the *reversed* fiber (or Type-B-like polarity), as the different ends of an MCF are naturally reversed, and 2-dimensional core layouts of MCFs cannot achieve *straight* fiber polarity without core shuffling

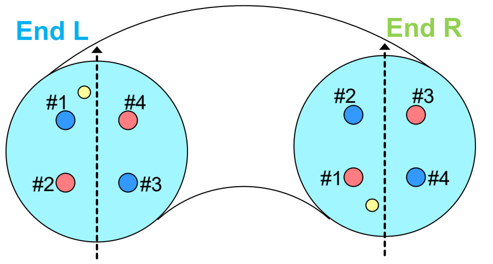

Fig. 5. Example of the 4-core fiber polarity different from reversed fiber polarity. End R is rotated by 180° from Fig. 1. This fiber polarity is similar to pairs flipped cable (Type C polarity in MPO cable).

waveguide or optics (i.e., the same core cannot go to the same port in the fiber cross sections at different ends). However, the square-layout 4-core fiber can achieve "pairs flipped" fiber polarity (like Type C polarity in MPO), as shown in Fig. 5. Therefore, if you need to have MCF cables with different polarities (for instance for polarity conversion for a specific type of transceivers), it is necessary to manage the cable/fiber polarity to ensure that cables with different polarities are not mixed up.

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